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Control of Turbulent Mixing Layers

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Study of the open-loop forcing of shear layer by a pitching airfoil led to the following results: (1) It is possible to induce very large changes in the shear layer growth rate downstream of the disturbance location, while leaving the portion of the layer between the splitter plate and the disturbance location essentially unaffected; (2) Upstream forcing can be used to modify the shear layer in the region upstream of the disturbance; (3) Two different mechanisms are responsible for coupling such disturbances to the flow in the cases of upstream and downstream forcing. An investigation into the structure of the wake of a pitching airfoil in a uniform stream revealed that the proper choice of the pitch oscillation parameters can result in significant alterations of the wake. In particular, flow regimes corresponding to wake, jet, double-wake and mixed jet-wake structures can be generated. Further study of the axial flow along the wake vortices indicated that the magnitude of the flow increases approximately linearly with both the amplitude and

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frequency of oscillation. The closed-loop feedback phase of the project was initiated by the demonstration of a cancellation experiment in a forced turbulent shear layer.

GRADUATE AERONAUTICAL LABORATORIES
CALIFORNIA INSTITUTE of TECHNOLOGY
Pasadena, California 91125

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** Presently, Assistant Professor, Dept. of Mechanical Engineering, Michigan State University.

Summary/Overview

This the final report of research conducted at the California Institute of Technology, by Paul E. Dimotakis, in collaboration with Dr. M. M. Koochesfahani† as co-investigator, and with the assistance of Mr. P. Tokumaru during the last year. The primary goal was to explore ways in which open loop and closed feedback loop control methods can be utilized to affect the qualitative and quantitative behavior of turbulent shear layers. In particular, we attempted to

i. investigate the dynamic behavior and response of these flows through a study of the feedback control schemes required to produce a given desired outcome,

ii. explore the extent to which specific properties of turbulent shear layer flows, such as growth rate profile and mixing, can be manipulated and altered by such means,

and,

iii. devise schemes for producing turbulent shear layer flows with specific desirable properties, as might be dictated, for example, by the flow specifications for the efficient operation of a combustion device.

In the course of this work, other derivative and closely related efforts were also undertaken, some of which will be described below.

The work conducted under the sponsorship of this Grant was primarily experimental and in close collaboration with a broader experimental, numerical and theoretical effort at Caltech to study unsteady separated flows‡, and the evaluation and use of control techniques in these flows in particular.

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† Presently at Michigan State University (East Lansing, Michigan).

‡ Under AFOSR URI Contract F49620-86-C-0134 sponsorship, with A. Roshko, A. Leonard as co-investigators, in close collaboration with J. Doyle (Professor, Dept. Electr. Engineering) and, in the final stages of the work reported here, in collaboration with P. Tokumaru (graduate student, Aeronauctics).

Technical discussion

In the case of our investigations under this Grant, we focused on issues of control of the flow in a two-dimensional, fully developed turbulent shear layer. The actuation scheme implemented used one (or more) pitching airfoil(s), either within the turbulent shear layer zone, and/or in the flow free stream. The formulation of an adequate flow model, as needed for the purposes of control, was one of the goals of the investigation.

The basic idea was to exploit the characteristics of the fully developed shear flow, *i.e.* the fact that the dynamically significant fluctuations are organized in the form of large scale spanwise (nearly) coherent vortical structures. Our original intent was to sense sufficient real-time information about the flow to be able to actuate the airfoil in pitch so as to control the shear layer behavior. Alternatively, and equally significant as a control option strategy, we attempted to *program* the flow behavior by injecting circulation perturbations into the flow, which grew in a controlled and predictable fashion, for the purpose of producing the desired shear layer behavior (see also discussion in Tokumaru & Dimotakis 1989). While for aspects of this work a linear stability analysis can serve as a useful model and guide (see references cited below and appended for a more complete discussion), what sets these efforts apart from classical control ventures is the fact that, generally speaking, the inherent non-linearity of the "plant", corresponding to the turbulent flow, *can not be treated as a perturbation on (or of) a model linear system*. This was already clear from the known response of a two-dimensinoal turbulent shear layer to external forcing, *e.g.* Oster & Wygnanski 1982, Ho & Huerre 1984, Roberts 1985, Roberts & Roshko 1985. We should note, however, that in the research documented in the preceding references the (open loop) actuation/disturbance was introduced at the shear layer splitter plate trailing edge.

It can be argued that feedback control used to move a splitter plate actuator will always drive the resulting flow to behave more like a (saturable) oscillator. Accordingly, we considered the use of a pitching airfoil that could be located anywhere in the flow. The relevant characteristics of such an actuation scheme, that might serve as a better candidate for both program and feedback control, were first examined in a separate investigation. More specifically, we initially explored the response of a uniform free stream flow to the influence of a pitching airfoil* by investigating the resulting wake characteristics for various pitching frequencies, amplitudes and pitching waveforms. That investigation proved interesting in its own right with a variety of new phenomena revealed by the novel degree of freedom afforded by the effect of a variable pitching *waveform*. These results were first presented

* NACA–0012, at low ($2^\circ - 4^\circ$) pitching amplitude, pivoting about the 1/4-chord point.

(Koochesfahani 1987, Appendix A) at the 25^{th} *AIAA Aerospace Sciences Meeting*, 12–15 January 1987 (Reno, Nevada).

The potential control authority of this actuation scheme over the turbulent shear layer was assessed by first investigating the *open loop* response of a turbulent shear layer to the pitching airfoil, located some distance downstream of the shear layer trailing edge. More specifically, the 1/4-chord point of the ($8\,cm$ chord) NACA–0012 airfoil was located 360 high speed boundary layer momentum thicknesses, θ_1, downstream of the splitter plate trailing edge and oscillated in pitch at various frequencies and amplitudes of a few degrees. Our results (Koochesfahani & Dimotakis 1987) were first presented at the 25^{th} *AIAA Aerospace Sciences Meeting*, 12–15 January 1987 (Reno, Nevada) and recently published in the *AIAA J.* (Koochefahani & Dimotakis 1989, Appendix B). They are in qualitative accord with previous, open loop shear layer (trailing edge) forcing experiments**. The fact, however, that the actuator is located some distance *downstream*, in this case, affords an important feature in the context of feedback control. We note, in particular, that

a. forcing at a frequency that is higher than the local large structure frequency at the airfoil location organizes the flow structure *upstream* of the pitching airfoil;

b. forcing at a lower frequency, can significantly increase the shear layer transverse extent† at a targeted *downstream* location.

Recall that fundamental control theory *precludes* forcing/actuation at the shear layer trailing edge for the purposes of *feedback* control of the turbulent shear layer at some downstream range.

To the extent that one would expect to be able to cancel existing disturbances, one might also expect to be able to cancel disturbances that are injected in a programmed manner into the flow. Accordingly, the next step was to use *two* airfoils. The first was located at $x = 24\,cm$ downstream of the splitter plate trailing edge to introduce a disturbance of a known frequency (and phase). The second was located at $x = 49\,cm$ and used in the attempt to cancel the disturbance introduced by the first, by actively controlling its oscillations in pitch. This is in the spirit of the boundary layer transition disturbance cancellation experiments of Liepmann & Nosenchuck (1982), *with the important difference*,

** See Ho & Huerre (1984) for a review, and Roberts (1985) and Roshko & Roberts (1985) for effects on mixing and chemical reaction.

† We have documented a *tripling*. We cannot say that this represents an upper bound, however, as the shear layer growth may have been limited by the location of the flow facility upper/lower walls.

however, *that this was undertaken here on fully developed turbulent flow* (Koochesfahani & Dimotakis 1988, Appendix C). Using the first airfoil only, we were able to recover the results of the previous investigation, namely the large increases in the shear layer growth at the targeted downstream location. Turning the second airfoil on in a negative feedback (cancellation) mode, we were able to effectively remove the disturbance (and its influence on the shear layer), effectively returning the flow state to that resulting from having the two airfoils stationary in place[‡].

These last experiments provide an important confirmation of the ideas on which the hope of feedback control of fully turbulent "natural" shear layers is founded. On the other hand, while this is an encouraging certification of the constitutive parts of such a control loop, we recognize that controlling a "natural" shear layer is quite a different matter. In particular, the *prediction* of the dynamics (*e.g.* frequency, amplitude and phase) of the primary disturbances we wish to control at the targetted downstream location, in the "natural" case, represents a formidable task. Accordingly, two possibilities may merit further investigations: the use of simplified non-linear models for the flow, or adaptively updated parametric system descriptions using linear models, in the sense of an adaptively updated local fit to the real-time non-linear dynamics of the real system.

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‡ Very close to (but not quite) a "natural" turbulent shear layer.

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Appendix A

AIAA'87

AIAA-87-0111
Vortical Patterns in the Wake of an Oscillating Airfoil

M. M. Koochesfahani, California
Institute of Technology, Pasadena, CA

AIAA 25th Aerospace Sciences Meeting

January 12-15, 1987/Reno, Nevada

VORTICAL PATTERNS IN THE WAKE OF AN OSCILLATING AIRFOIL

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Abstract

The vortical flow patterns in the wake of a NACA 0012 airfoil pitching at small amplitudes are studied in a low speed water channel. It is shown that a great deal of control can be exercised on the structure of the wake by the control of the frequency, amplitude and also the shape of the oscillation waveform. An important observation in this study has been the existence of an axial flow along the cores of the wake vortices. Estimates of the magnitude of the axial flow suggest a linear dependence on the oscillation frequency and amplitude.

Introduction

The classical unsteady aerodynamic theory of oscillating airfoils[1,2] was developed as a result of interest in aircraft flutter problem. This theory later found extensive use in biofluiddynamics since the propulsion of certain species of birds, insects and aquatic animals is characterized by a heaving and pitching motion of a high aspect ratio wing or fin[3,4]. The main ingredients of the classical analysis are the two-dimensional potential flow along with linearized boundary conditions, small perturbation velocities and the assumption of a planar vortex wake. The effects of non-linear processes such as rolled-up wake patterns have been addressed using numerical techniques[5-7].

In comparison with the many theoretical and numerical studies that have been devoted to the subject of oscillating airfoils, there appear to be quite few experimental results available. Among the available experimental investigations, most have concentrated on measuring the forces on oscillating wings[8-10], while studying the characteristics of the wake seems to have received lesser attention. Bratt's[11] smoke flow visualization of the vorticity roll-up in the wake of a wing performing rolling oscillation is one of the earliest works on wake flow patterns and has been used for verification of the numerical techniques mentioned above.

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Sinusoidal oscillation of an airfoil has been the traditional form of periodic oscillation studied theoretically, numerically and experimentally. In the present work, the effect of both sinusoidal and nonsinusoidal shape of the waveform on the vortical patterns in the wake of a pitching airfoil is investigated. Qualitative features are determined from flow visualization pictures. Laser Doppler velocimetry is utilized to obtain quantitative measurements of the mean streamwise velocity component. Using the velocity profiles, the dependence of the airfoil drag/thrust on the oscillation amplitude and frequency is determined. The existence of an axial flow along the cores of the wake vortices is pointed out. Its origin and dependence on the oscillation amplitude and frequency are discussed.

Experimental Facility & Instrumentation

These experiments were performed in the Low Speed Water Channel of the Graduate Aeronautical Laboratories of California Institute of Technology (GALCIT). The airfoil was based on the NACA 0012 wing section with a chord of C = 8 cm, a span of b = 39 cm and was pivoted about the 1/4-chord point. The airfoil was fitted with end plates since, due to mechanical linkage requirements, the span was smaller than the channel width (45 cm). A shaker coil mechanism in conjunction with a closed-loop feedback servosystem drove the airfoil to the desired angular position in pitch (see figure 1). With this setup, the airfoil angular position followed a command signal which, for these measurements, originated from a function generator (HP3314A). The mean angle of attack, the amplitude A, the frequency f, and the shape of the oscillation waveform could, in this way, be independently controlled.

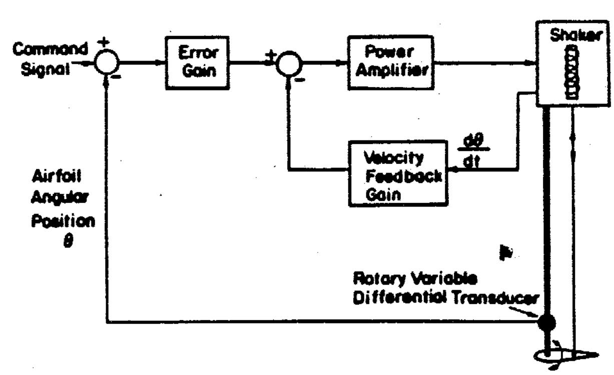


Fig. 1 Schematic of servosystem for control of airfoil angular position.

The effect of nonsinusoidal oscillation is demonstrated in terms of a symmetry parameter, S, which is the percentage of a period (in one cycle) required to reach the maximum amplitude starting from the minimum amplitude. When S=50% the waveform is sinusoidal whereas a value of S larger (smaller) than 50% corresponds to a slower (faster) rate of pitch-up than pitch-down. See figure 2 for sample waveform shapes.

The wake flow was visualized using food-coloring issued from small injection tubes imbedded in the airfoil trailing edge and was subsequently recorded on photographic film by a 35 mm camera. The streamwise component of the velocity vector was measured by a single-channel, frequency-shifted laser Doppler velocimeter (LDV) in the dual scatter mode. The Doppler burst was processed by a Tracking Phase-Locked Loop (in-house design by P.E. Dimotakis) whose output frequency was measured by a Real Time Clock card interfaced to a PDP-11/73 computer.

Results & Discussion

For the results reported here, the free-stream velocity was approximately U_∞ = 15 cm/sec, resulting in a chord Reynolds number of 12,000 and a reduced frequency of $k = 2\pi fC/2U_\infty = 1.67$ (f/Hz). The mean angle of attack was set to zero so that the angle of attack of the airfoil varied between -A & A, A being the amplitude of pitch waveform.

Sinusoidal Oscillation

The sequence of pictures in figure 3 shows the dependence of the wake structure on the oscillation frequency for a sinusoidal (S=50%) pitch waveform. The flow is from right to left and the downstream distance visible on the photographs corresponds to approximately 3.75 chord lengths. It can be seen that, at low frequencies, a smoothly undulating wake is formed which carries the Karman vortices shed by the natural wake. At higher values of the frequency, the wake displays characteristic vortex patterns similar to those observed by Bratt[11] and Thomas & Whiffen[12]. Numerical calculations of Katz & Weihs[13] have suggested a value for the critical reduced frequency, k > 2, above which the wake rolls up into vortex structures. Even though this value agrees with the data of figure 3, caution should be exercised in this comparison. We have generally observed that the frequency for vortex roll-up decreases as the oscillation amplitude increases. One would expect a similar behavior to exist in numerical calculations. Therefore, the use of a universal critical reduced frequency does not seem to have much significance.

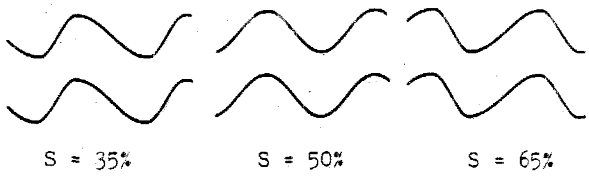
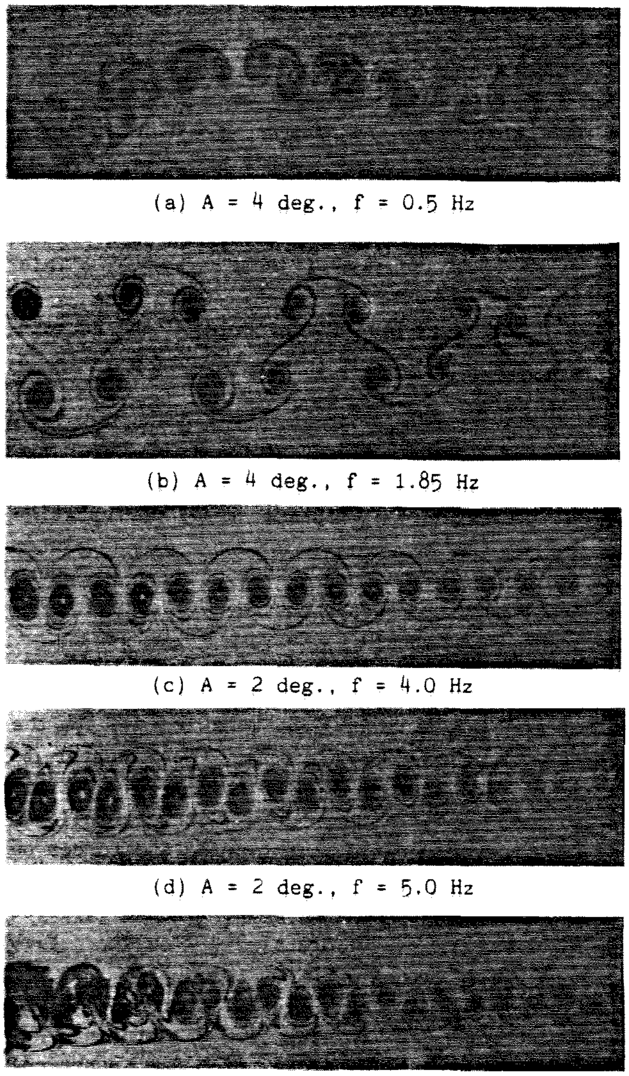


Fig. 2 Examples of pitch waveforms
Upper trace : airfoil angular position
Lower trace : command signal.



(a) A = 4 deg., f = 0.5 Hz

(b) A = 4 deg., f = 1.85 Hz

(c) A = 2 deg., f = 4.0 Hz

(d) A = 2 deg., f = 5.0 Hz

(e) A = 2 deg., f = 6.0 Hz

Fig. 3 Wake of a NACA 0012 airfoil pitching sinusoidally about 1/4-chord point. Flow is from right to left.

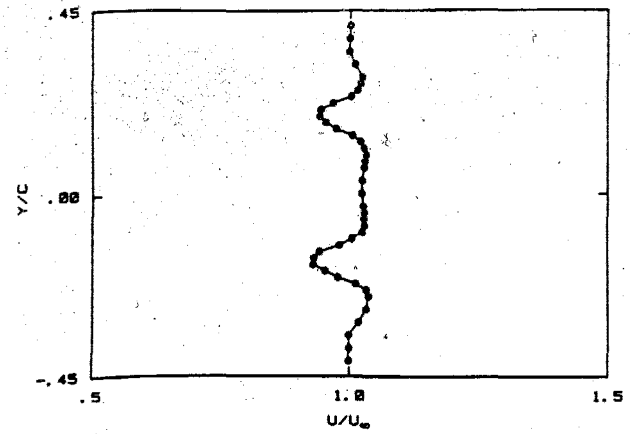


Fig. 4 Mean velocity profile at X/C = 1 for the case in figure 3(b).

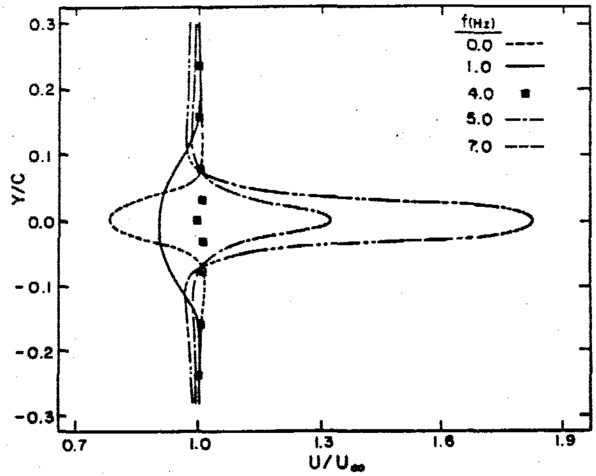


Fig. 5 Mean velocity profiles in the wake of a sinusoidally pitching NACA 0012 airfoil (X/C = 1).

Figure 3(b) shows a special case where two vortices of the *same sign* are shed on each half-cycle of the oscillation. The mean velocity profile for this case, figure 4, shows that this vortex pattern corresponds to a double-wake structure. The pattern remained stable (i.e. fixed pattern) all the way to the farthest downstream distance (X/C ≈ 30) at which the wake was observed. A similar stable configuration could not be sustained at low amplitudes (e.g. less than 2 degrees). At higher amplitudes, it was possible to generate a stable pattern consisting of three same-sign vortices shed per half-cycle of the oscillation.

Once the frequency is high enough, an alternating vortex pattern is formed such that the vortex with a positive (counter-clockwise) circulation is located on top and the one with negative circulation on the bottom, see figure 3(d,e). This arrangement is opposite that of a typical Karman vortex street observed in wakes and, in fact, this pattern corresponds to a "jet". The mean velocity profiles measured at X/C = 1, shown in figure 5, also confirm this behavior. In this figure, it can be seen that the usual wake profile with velocity deficit (i.e. an airfoil with drag) can be transformed into a wake with velocity excess (no longer a wake but actually a jet, i.e. an airfoil with thrust) above a certain frequency. It should be noted that the jet-like vortex pattern corresponding to a thrust-generating body is a well-known phenomenon and was described by Von Karman & Burgers[14] for the case of a flat plate in transverse oscillation.

Figure 5 also shows that there exists a condition (A=2 degrees, f=4 Hz) at which the wake has no momentum deficit or excess (i.e. an airfoil with no drag). This condition occurs when the alternating vortices are positioned exactly on a straight line as seen in figure 3(c). The vortex pattern showed no tendency to deviate from this alignment as it moved downstream. As a result of this, the mean velocity profile, U, measured at X/C = 3 (not show here) was also approximately uniform at the free-stream value much the same way as at X/C = 1 (see figure 5). Note that this implies that the gradients of U in both streamwise and transverse directions are nearly zero for this special case.

The mean velocity profile U(y) can be used to estimate the mean streamwise force on the airfoil. With the usual normalization of the force with the free-stream dynamic head and the airfoil chord, the force coefficient is given by

$$C_F = \frac{2}{C} \int_{-\infty}^{\infty} \frac{U}{U_\infty} \left(\frac{U}{U_\infty} - 1 \right) dy \ ,$$

where the contributions due to the fluctuating quantities and the pressure term have been neglected. A negative value of C_F corresponds to drag and a positive value implies thrust. A plot of C_F versus reduced frequency is shown in figure 6 for two oscillation amplitudes of two and four degrees. The classical theory[15] indicates that the inviscid oscillation of a flat plate around the 1/4-chord point starts producing thrust at a critical reduced frequency of about k = 1. We note, however, that in the present experiment thrust is produced at a higher reduced frequency. This discrepancy may be expected since here there is a substantial viscous drag to be overcome, which does not of course exist in the inviscid case. Also, within the linear assumptions of the theory, the oscillation amplitude does not affect the predicted critical value of k, in disagreement with the data of figure 6. Even though one might

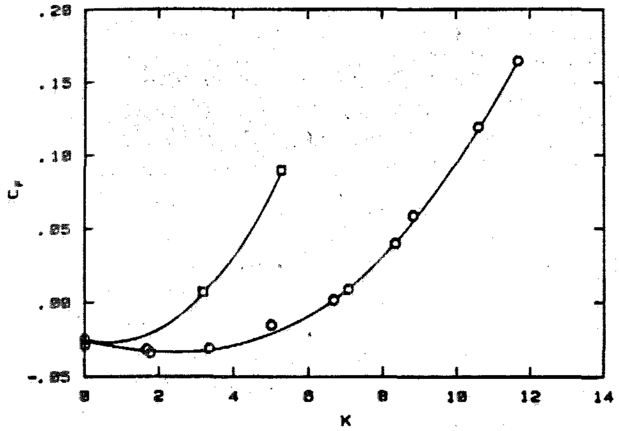
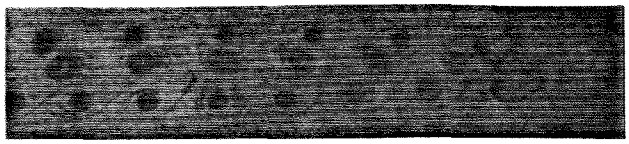


Fig. 6 Variation of force coefficient with reduced freqeuncy.
○ A = 2 deg. □ A = 4 deg.

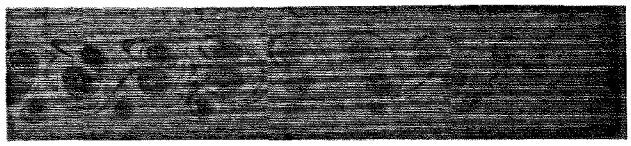
be tempted to interpret the observed effect of the amplitude as a truly nonlinear effect, other difficulties complicate the issue. Before any comparison between the present low Reynolds number case and inviscid calculations can be attempted, it may be necessary that the oscillation amplitude be "reasonably" large compared to, say, the boundary layer thickness at the airfoil trailing edge. In support of this, it should be mentioned that when the oscillation amplitude was reduced to one degree, no evidence of thrust was found up to k = 11. Conversely, the amplitude cannot become "too" large if a comparison with a linear theory is to be sensible. It is not presently clear at what amplitude a fair comparison between this experiment and inviscid theory should be made.

Nonsinusoidal Oscillation

The shape of the pitch waveform has a strong effect on the vortical patterns in the wake as demonstrated in figure 7. At a given frequency, by simply changing the shape of the waveform, it is possible to generate a variety of complex vortex-vortex interactions. The general observation is that a single strong vortex is formed during the fast part of the cycle, whereas more than one vortex (of the *same* sign) form on the slow cycle. For example, in figure 7(a), two vortices of the same sign are shed during the slow cycle. The number of vortices shed during the slow cycle increases with the oscillation amplitude as can be seen in figure 7(b). Note, in this figure, how the pairing events are modified and delayed as the waveform shape changes slightly. It is known that the motion of more than three point vortices is sensitive to the initial conditions and could result in chaotic motions (see Aref[16]). The strong dependence of the wake vortex pattern on the initial conditions which are observed here may be a related phenomenon. Figure 7(c) shows a particularly interesting case where a single vortex on top goes through the wake and ends up on the bottom unscathed.



S = 61%

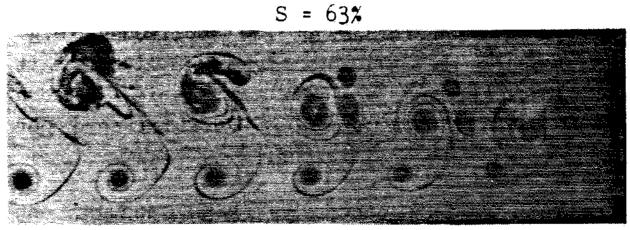


S = 38%

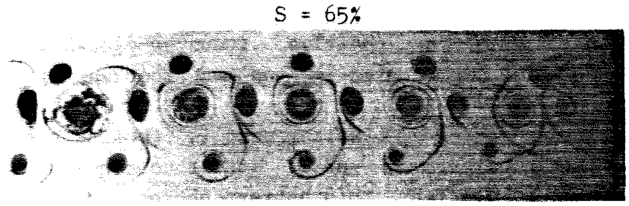
(a) A = 2 deg., f = 4.0 Hz

S = 61%

S = 63%

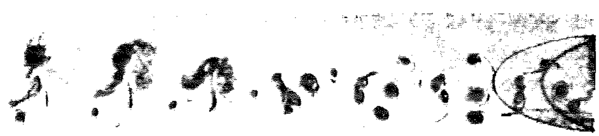


S = 65%



S = 67%

(b) A = 4 deg., f = 3.0 Hz



(c) A = 4 deg., f = 3.0 Hz, S = 30%

Fig. 7 Wake patterns for nonsinusoidal oscillation waveform.

These modifications of the wake structure occur as a result of the manipulation of the strength (circulation) and spacing of the vortices shed into the wake, which subsequently convect and interact by inviscid vortex interactions. To the extent that these vortices are the carriers of momentum and energy in the wake, the load history on the airfoil may be expected to be strongly affected. Figure 8 shows an example of the extent of the wake modification as displayed by the mean velocity profile measured for the case S=38% of figure 7(a). It can be seen that in the same "wake" both wake and jet structures are present. This peculiar behavior becomes readily apparent upon inspection of the arrangement of the vortices for this case (see the close-up accompanying figure 8).

Axial Flow along Vortex Cores

The wake is generated here by two-dimensional motions of a geometrically two-dimensional body. The resulting flow, however, is not two-dimensional and an axial flow exists along the cores of the wake vortices, see figure 9. The four dye streaks in this plan view of the wake were placed roughly symmetrically with respect to the water channel centerline are were approximately one chord length apart. The axial flow takes the form of a spiralling out of the vortex core fluid away from the channel side walls toward the channel centerline. Evidence of this type of flow three-dimensionality can also be found in the flow visualization pictures of Cornish[17] and in the rolling wing experiment of Bratt[11] where he states that "vortices were seen to be spiralling out in a spanwise direction from root to tip".

The magnitude of the axial flow appears to depend on both the frequency and amplitude of oscillation and is believed to be tied directly to the vortex circulation. For example, figure 9 shows the increase of the axial velocity when the frequency is increased. This is manifested by the shortening of the distance downstream of the airfoil trailing edge where the axial flow in the vortices reaches the channel centerline. The dependence of this distance, denoted by L, on the oscillation frequency was derived from plan view photographs and is shown in figure 10. An estimate of the average axial flow velocity, W, along the vortex cores is presented in figure 11. The values of W were calculated from the L/C data of figure 10 assuming a constant axial speed and a vortex convection speed of U_c using the relation $W/U_c = 1.9/(L/C)$. The constant 1.9 is a geometric factor resulting from the positions of the dye

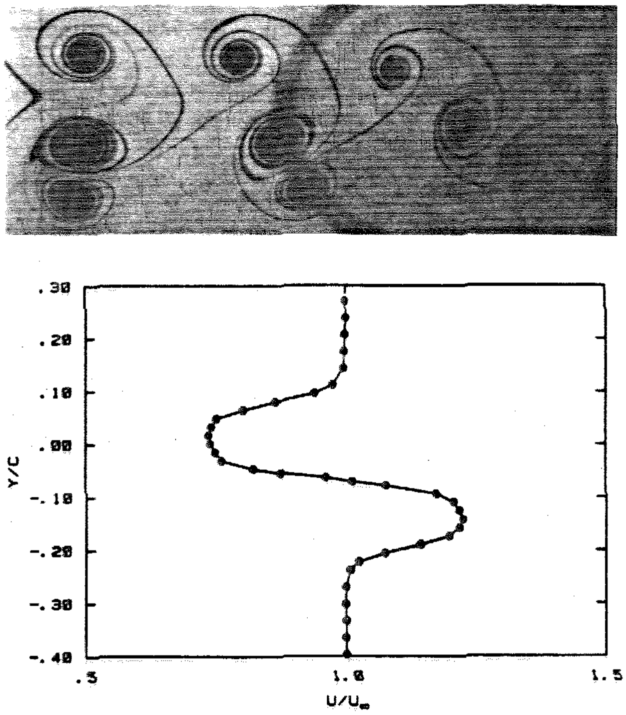
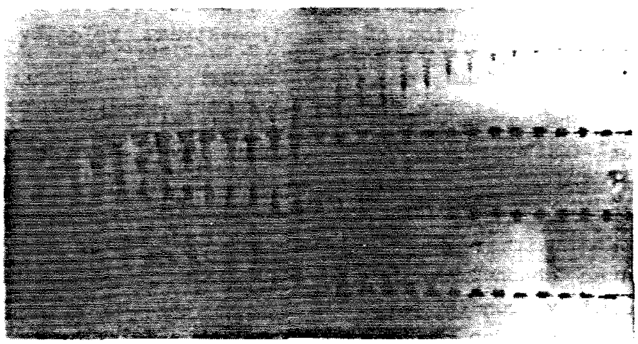
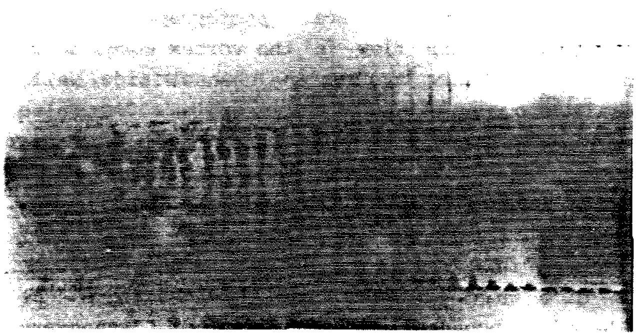


Fig. 8 Mean velocity profile at X/C = 1 for the case in figure 7(a); S = 38% and the corresponding vortex arrangement (top photo).



A = 2 deg., f = 4.5 Hz



A = 2 deg., f = 5.5 Hz

Fig. 9 Axial flow along vortex cores (sinusoidal oscillation).

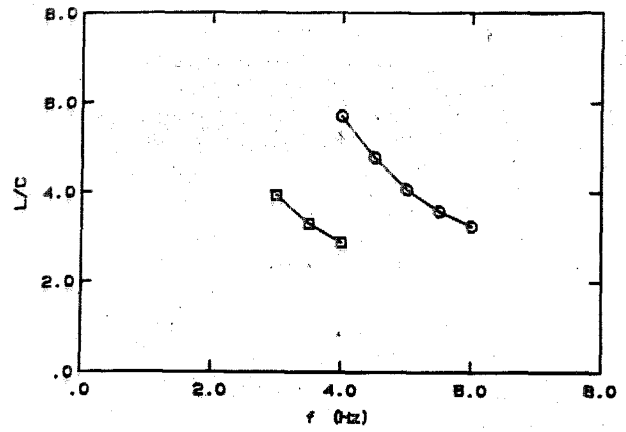


Fig. 10 Estimate of the downstream distance where the axial flow in the vortex cores reaches the channel midspan.

○ A = 2 deg. □ A = 4 deg.

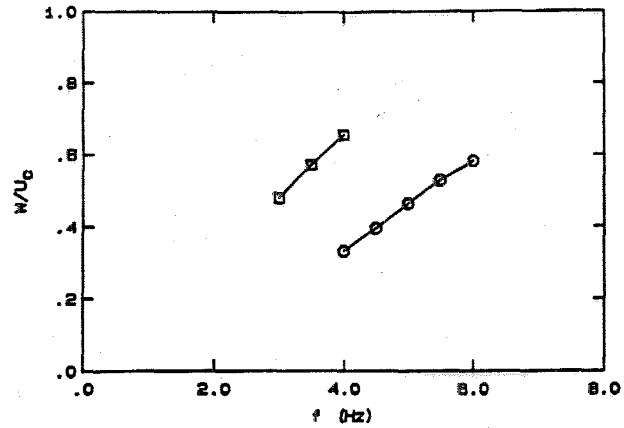
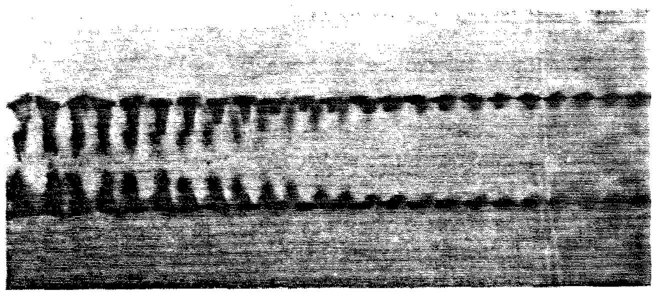


Fig. 11 Estimate of the magnitude of the axial velocity along vortex cores.

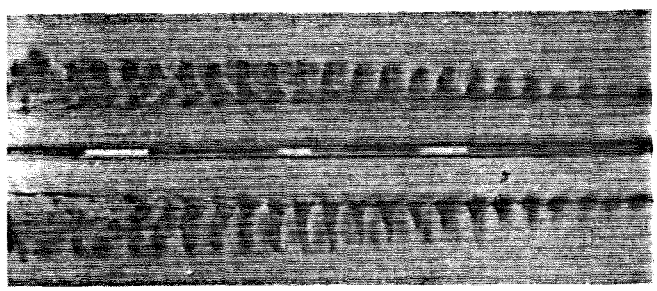
○ A = 2 deg. □ A = 4 deg.

streaks in the plan view picture (e.g. see figure 9). For the range of parameters studied here, the vortex convection speed U_c varies very little and is close to the free-stream speed U_∞ so that W/U_c in figure 11 is approximately equal to W/U_∞. The data in figure 11 indicate that the magnitude of the axial speed increases almost linearly with the oscillation frequency. Comparing results at the same frequency (f = 4 Hz) and two different amplitudes suggest a linear dependence on the amplitude also. It should be noted that the magnitude of the axial flow can be a sizable fraction of the free-stream velocity ($W/U_\infty \approx 0.65$).

The nature of the vortex core axial flow is not fully understood. It is believed that the axial flow is initially generated due to the interaction of a concentrated two-dimensional vortex with a bounding wall (in this case, the water channel side walls). That the no-slip boundary condition at the wall is the major ingredient for the initiation of the axial flow is shown in figure 12. This plan view of the wake is similar to figure 9 except that only the middle two dye streaks are photographed. In figure 12(a), the flow in the vortex cores moves in the direction away from the channel side walls similar to figure 9. Upon insertion of a false wall in between these two dye streaks, figure 12(b), the flow direction is reversed. The magnitude of the axial flow appears to be the same with or without the false wall. Hence, it is only necessary that the no-slip condition be present on the side walls and the actual thickness of the side-wall boundary layers is of secondary importance. We mention here that a strong effect of side walls has also been observed in the forced wake (by oscillating one free-stream) behind the trailing edge of a splitter plate under certain



(a) without false wall



(b) with false wall

Fig. 12 Effect of a false wall on the axial flow in the vortex cores, A = 2 deg., f = 4.0 Hz, sinusoidal oscillation.

forcing conditions[18]. There, however, it appears that the entire flow in the channel is affected and moves away from the side walls. In the present case, the axial flow exists only within the vortex cores and the vortices themselves are not "bent away" from the side walls (see figure 9).

Once the axial flow is initiated at a wall, it seems to propagate along the core of the vortex in a wave-like manner. This feature may have a connection with the recent theoretical work of

Lundgren & Ashurst[19]. In figure 9, it is seen that the predominant axial flow is away from the channel side wall toward the channel mid-plane for *all* the vortices. We have observed cases where the direction of the axial flow depends on the sign of the circulation of the vortex. This generally happens only in the downstream region corresponding to the first few periods of oscillation and as the vortices move farther downstream the axial flow along all the vortices will move in the same direction.

Conclusions

The structure of the wake of a pitching airfoil can be substantially modified by the control of the amplitude, frequency and also the shape of the oscillation waveform. At a given frequency and amplitude, a variety of complex vortex-vortex interactions can be generated by simply changing the shape of the waveform. It is found that the pitching airfoil in this experiment produces thrust at a higher reduced frequency than that indicated by the calculations based on the classical linear inviscid theory. In addition, the value of the critical reduced frequency for thrust generation appears to depend on the oscillation amplitude. An axial flow is observed along the core of the wake vortices. Results suggest that the magnitude of the axial flow increases approximately linearly with both the amplitude and frequency of oscillation. It is argued that the axial flow is the result of the no-slip boundary condition enforced on the wake vortices by the channel side walls. The details of this flow, particularly its wave nature, require further work.

The types of wake modification that have been demonstrated in this work need to be pursued further in order to find out their effects on the body itself (e.g. lift and drag). Furthermore, the independent control of the various parameters of the oscillation waveform provides an excellent opportunity to produce many interesting and complicated vortex patterns whose stability and interactions are worthy of study in their own right.

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Appendix B

Effects of a Downstream Disturbance on the Structure of a Turbulent Plane Mixing Layer

M. M. Koochesfahani and P. E. Dimotakis

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Effects of a Downstream Disturbance on the Structure of a Turbulent Plane Mixing Layer

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Using a two-dimensional airfoil, a disturbance was introduced into a plane mixing layer some distance downstream of the splitter plate trailing edge. Results indicate that it is possible to induce very large changes in the layer growth rate downstream of the disturbance location, while leaving the portion of the shear layer between the splitter plate and the disturbance source essentially unaffected. Furthermore, the use of forcing for modification of the mixing layer in the region upstream of the disturbance is demonstrated. It is shown that two different mechanisms are responsible for coupling such disturbances to the flow in the present forcing of upstream and downstream regions.

Introduction

It is known that the evolution of plane mixing layers can be strongly affected by low-amplitude disturbances. As a result of the sensitivity of shear layers to initial conditions, most of the effort has been concentrated on modifying the initial shedding of vorticity through artificial excitation. These and other related phenomena have been reviewed by Ho and Huerre.[1] Forcing is usually achieved by introducing disturbances acoustically,[2,3] mechanically by oscillating a trailing-edge flap,[4] or oscillating one or both freestream velocities.[5-7] Other methods such as the strip-heater technique have also been used.[8]

The common feature of forcing studies to date is that the disturbances are effectively introduced at the tip of the splitter plate. As a result of this, the entire region of the flow downstream of the splitter plate is modified. Experimental results[4,5] show that the forced shear layer exhibits three distinct response regions (see also Refs. 1 and 9). In region 1, the layer growth rate is enhanced by up to a factor of about two[9] compared to the unforced case. The mixing layer spreading rate remains virtually constant in region 2. This region is characterized by a single array of equally spaced large vortical structures that do not interact with one another. And finally, region 3 marks the gradual relaxation to the growth rate characteristics of the unforced mixing layer.

In the work described in this paper, we consider the case where a two-dimensional disturbance is introduced into a turbulent mixing layer at some distance downstream of the trailing edge of the splitter plate. The response of the mixing layer in the regions both upstream and downstream of the location of the disturbance source is investigated using flow visualization and laser Doppler velocimetry.

Experimental Facility and Instrumentation

This work was carried out in a low-speed, free-surface water channel. The test section was 45.72 cm wide and 42 cm high (dictated by the height of the water in the channel). In the present study, the first 210 cm of the over 300-cm-long test section was utilized. The water channel was modified to generate a high-aspect-ratio two-dimensional shear layer, as indicated in Fig. 1. The special insert used for this purpose followed the design of Dimotakis and Brown[10] and produced a shear layer with a velocity ratio, $r = U_2/U_1$, of approximately 0.44. In this design, the insert accelerated the flow below it and decelerated the flow above it. A perforated plate and a screen placed in the upper part of the insert were responsible for a head loss that matched the Bernoulli pressure drop in the lower part of the flow. This matching was necessary in order to avoid separation at the leading edge of the insert. For further details of the design, the reader is referred to Ref. 10. The details of the perforated plate and screen that were selected and the resulting flow characteristics are described by Lang.[11]

The velocity of the high-speed stream was set to $U_1 \approx 20.6$ cm/s, resulting in a Reynolds number, based on $\Delta U = U_1 - U_2$, of about 1150/cm. The boundary layer on the high-speed side at the splitter plate tip was found to be laminar with a momentum thickness of $\theta_0 = 0.76$ mm. The natural vortex formation frequency f_0, under these operating conditions, was about 6 Hz. This was determined from the peak of the spectrum of the streamwise velocity fluctuations close to the splitter plate tip. Throughout this paper, x refers to the streamwise coordinate measured from the splitter plate tip and y to the cross-stream direction (see Fig. 1).

Disburbances were generated by a pitching NACA 0012 airfoil that extended across the span of the water channel test section. The pitch axis was at the quarter-chord point and the airfoil chord was $C = 8$ cm. The driving mechanism was designed such that the airfoil could execute any arbitrary waveform shape.[12] For the results presented here, however, only sinusoidal oscillations were considered. The mean angle of attack relative to the shear layer freestream velocity vector was set to approximately zero. As an indication of the disturbance amplitude, we use the airfoil angle-of-attack amplitude A in degrees (i.e., airfoil angle of attack varies between $-A$ and A). For the range of values of A used here, the amplitude of the trailing-edge excursion in millimeters turns out to match the A values to within 5%.

The flow was visualized using food coloring issued from an injection port imbedded in the high-speed side of the shear layer insert and was subsequently recorded on photographic film by a 35 mm camera. The streamwise component of the velocity vector was measured by a single-channel, frequency-shifted laser Doppler velocimeter (LDV) in the dual scatter mode. The Doppler burst was processed by a tracking phase-locked loop (in-house design by P. E. Dimotakis) whose output frequency was measured by a real-time clock card interfaced to a data acquisition system based on a PDP 11/73 CPU.

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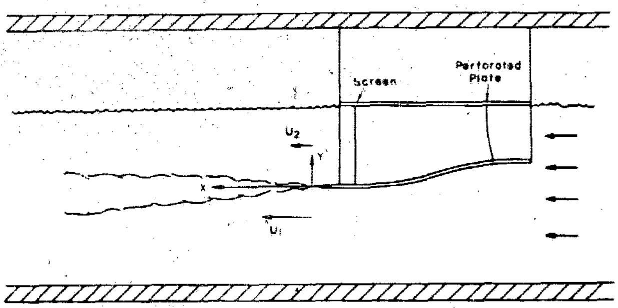


Fig. 1 Schematic of the shear layer insert.

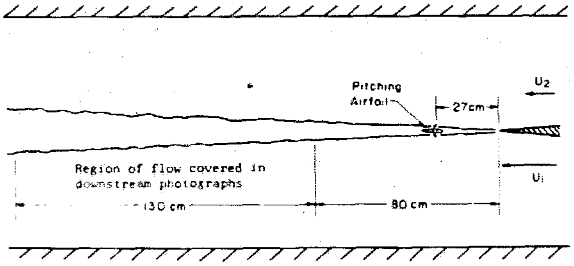


Fig. 2 Flow geometry in forcing experiments.

Results and Discussion

For the results described here, the airfoil was placed roughly in the middle of the shear layer at a downstream distance of 27 cm as measured by the distance between the airfoil pitch axis (quarter chord) and the trailing edge of the shear layer splitter plate; see Fig. 2. At this separation distance, the presence of the airfoil did not affect the characteristics of the otherwise natural layer in the region between the splitter plate and the airfoil. The initial instability frequency f_0 and the mean and rms profiles of the streamwise velocity component remained unchanged in this region, with or without the airfoil.

Throughout this paper, we use an integral thickness as a measure of the shear layer local thickness, defined by

$$\theta = \int_{-\infty}^{y_m} \left[\frac{U_1 - U(y)}{U_1 - U_m}\right]\left[\frac{U(y) - U_m}{U_1 - U_m}\right] \mathrm{d}y$$

where $U(y)$ is the mean streamwise velocity profile, U_m the minimum velocity in the profile, and y_m the y location where $U = U_m$. This definition was suggested by Lang[11] to accommodate mean profiles with a wake component. Note that when the wake component goes to zero, resulting in $U_m \to U_2$ and $y_m \to +\infty$, the usual definition of the integral thickness is recovered.

Downstream Influence

The general effect of the pitching airfoil on the shear layer in the region downstream of the airfoil is illustrated in Fig. 3. The right and left edges of each photograph correspond to a range of downstream stations of $80 < x < 210$ cm measured from the splitter plate trailing edge. This range is equivalent to $1053 < x/\theta_0 < 2763$, where θ_0 is the initial momentum thickness of the boundary layer on the high-speed side at the splitter plate tip. The width of each photograph in the cross-stream direction corresponds to the height of the water in the channel, approximately 42 cm in this case.

Figure 3 shows that large increases in the layer growth rate can be achieved at low forcing frequencies ($f/f_0 \ll 1$). Note that the mere presence of the nonoscillating airfoil in the layer (Fig. 3b, $f = 0$) appears to have reduced the layer growth rate.

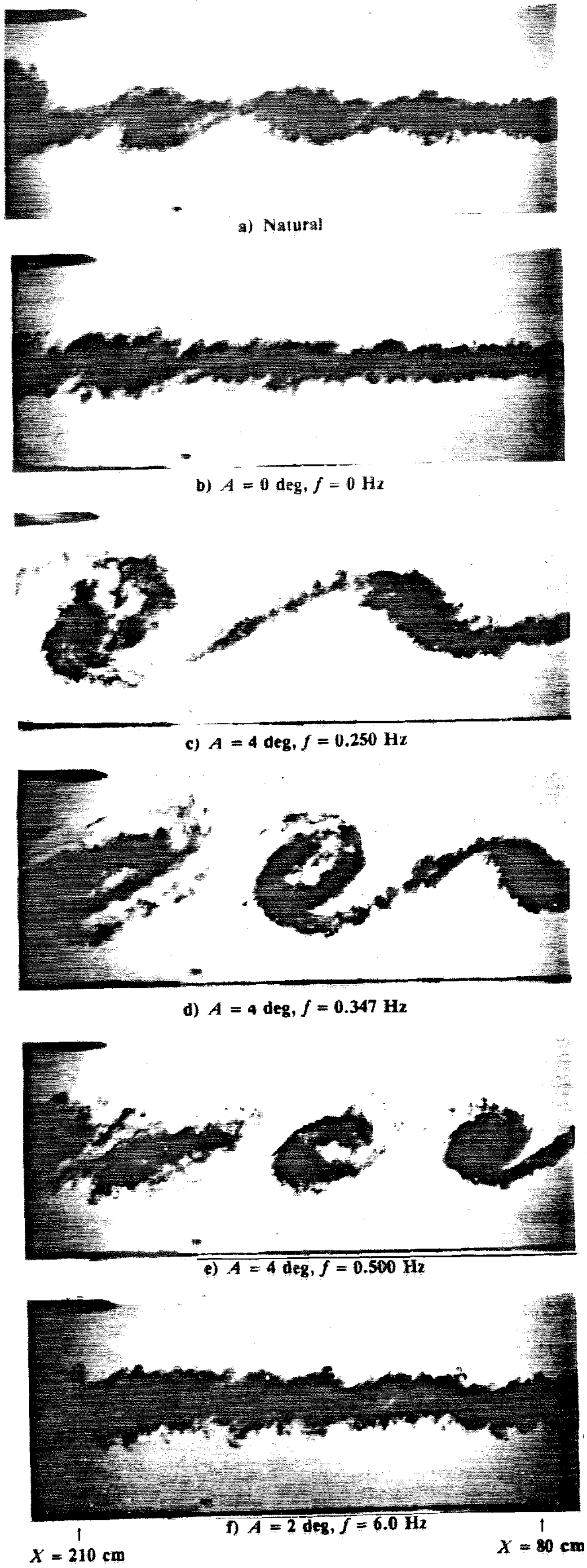


Fig. 3 Effect of the pitching airfoil on the shear layer structure and growth in the region downstream of the airfoil (flow is from right to left).

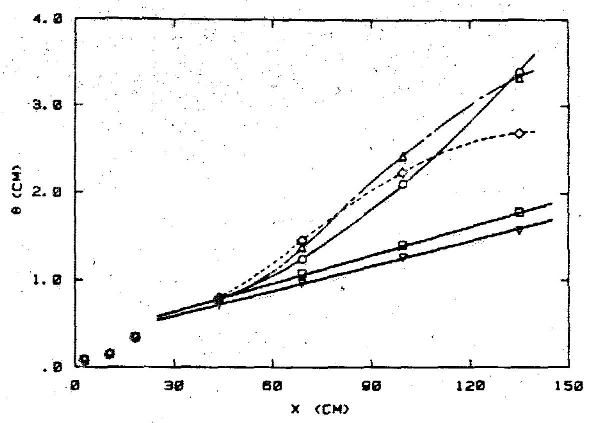


Fig. 4 Variation of the shear layer thickness for A = 4 deg (□ natural; ▽f = 0, A = 0; ○f = 0.250; △f = 0.347; ◇f = 0.500).

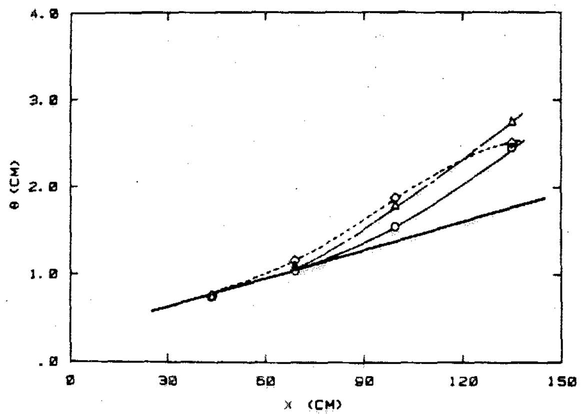


Fig. 5 Variation of the shear layer thickness for A = 2 deg (—— natural, ○f = 0.250, △f = 0.347, ◇f = 0.500).

Similarly, in the case of a high oscillation frequency (f = 6), the shear layer seems to grow more slowly than the natural case. It should be mentioned that, for high-frequency cases, the airfoil oscillation amplitude was lowered in order to keep the acceleration at these high frequencies manageable, particularly during long periods of time required for data acquisition. No discernible difference was observed upon increasing the amplitude from 2 to 4 deg in the case of high-frequency forcing.

These qualitative results are further substantiated by velocity profile measurements. See the θ vs x plots in Fig. 4, which were computed from these profiles (Figs. 8, 12, and 14 represent typical profiles). This figure includes only low-frequency forcing results, since that is when the largest effects were observed. When the stationary airfoil is in the layer, the downstream growth rate is reduced by approximately 15% relative to that of the natural layer. At this point, it may be interesting to note the qualitatively similar behavior of turbulent boundary layers resulting from the insertion of large-eddy breakup devices.[13] Whether the reduction of the shear layer growth rate can be explained by similar mechanisms and whether this reduction persists at large downstream distances requires further study. We also note that the downstream growth rate of the layer at high forcing frequencies (results not shown here) tends to be lower than the natural case and is bracketed between the growth rates of the natural layer and the layer with the stationary airfoil.

Results obtained at forcing frequencies of f = 0.25, 0.347, and 0.50 indicate that low-frequency forcing is characterized by an increase of the shear layer spreading rate culminating in

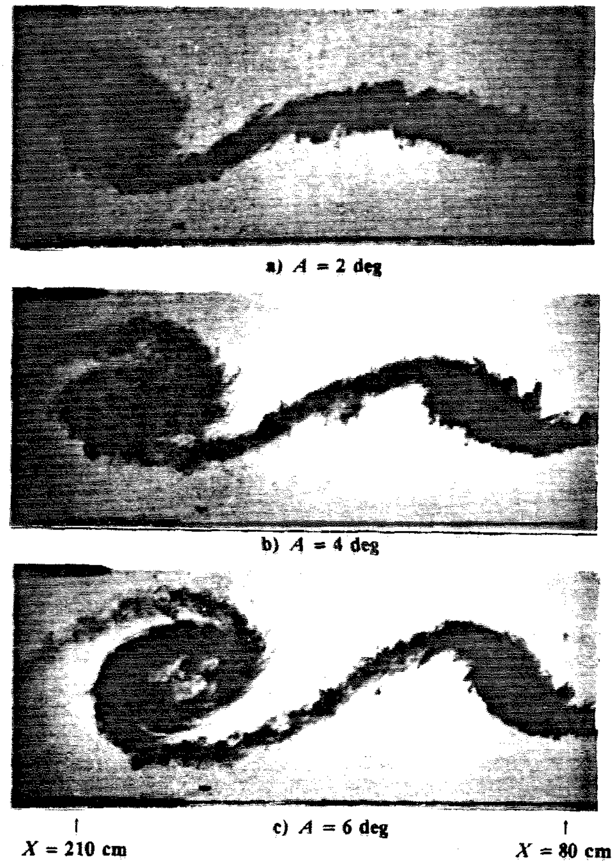


Fig. 6 Effect of the forcing amplitude on the shear layer structure and growth for f = 0.250 Hz.

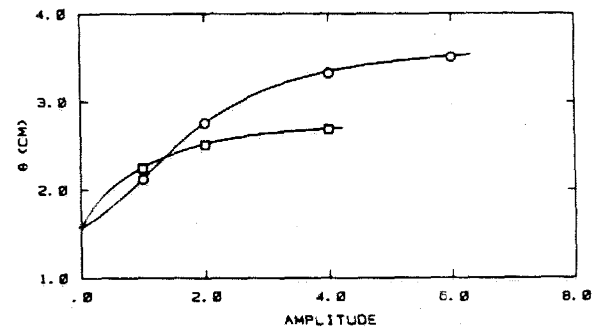


Fig. 7 Variation of the shear layer thickness with forcing amplitude at X = 135 cm (○f = 0.347, □f = 0.500).

the formation of large vortices. The enhanced growth is not linear in x and its magnitude depends on the forcing frequency (e.g., see Fig. 4). As the frequency decreases, the region of flow showing increased growth moves downstream and the final vortex formed has a larger size. It appears that the growth of the forced layer becomes very small once the associated large vortices are formed. This can be seen in the photographic data (Fig. 3) and the trend in the θ vs x plot (Fig. 4) as x increases.

The forcing amplitude affects the features described above in the following way. An increase (decrease) of the airfoil pitch amplitude increases (decreases) the layer spreading rate and causes the final large vortex to be formed somewhat earlier (later). These effects are shown in Fig. 5 (to compare with Fig. 4) and Fig. 6. One consequence of these events is that, as the forcing amplitude is raised, the shear layer thickness, at a fixed downstream location, increases and ultimately reaches a "saturation" value; see Fig. 7. It is not clear, at this

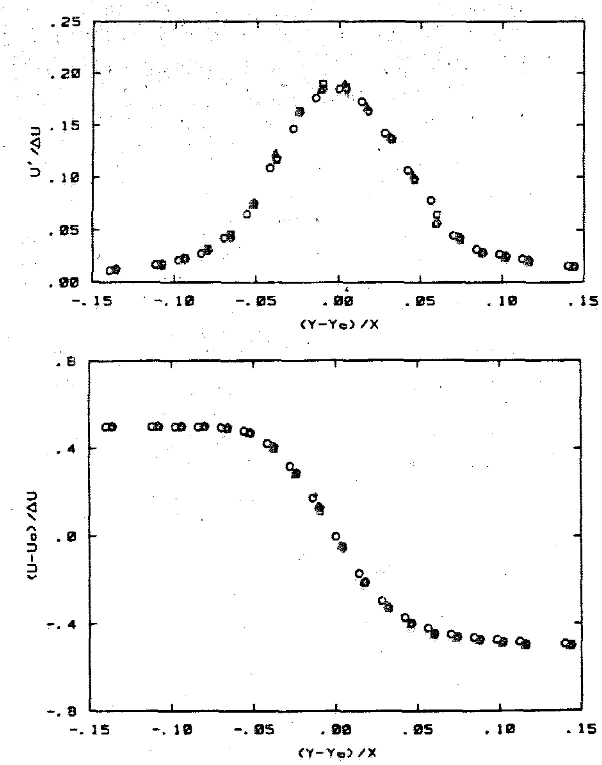


Fig. 8 Mean and rms velocity profiles at $X = 18$ cm (○ natural; □ $A = 0, f = 0$; ◇ $A = 4, f = 0.250$; △ $A = 4, f = 0.500$).

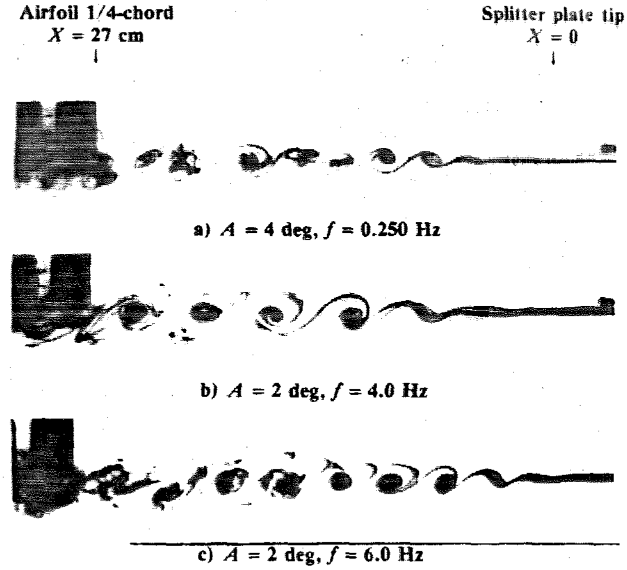


Fig. 9 Effect of the pitching airfoil on the shear layer structure and growth in the region upstream of the airfoil.

point, whether this saturation is due to the layer growth rate having reached a limiting value or the moving upstream of the location of vortex formation.

Results from Fig. 3 ($f = 0.25$, 0.347, 0.5) and also Fig. 9 (discussed in the next section) suggest that, for a given airfoil oscillation frequency, the shear layer thickness reaches a maximum at a downstream station x where the final large vortices are fully formed. This station seems to be the location where the mean vortex passage frequency of the natural layer roughly matches the forcing frequency. If $\overline{l}_n$ denotes the mean vortex spacing at downstream station x in the natural layer, the mean vortex passage frequency $\overline{f}_n$ can be calculated from $\overline{f}_n = U_c/\overline{l}_n$. The convection speed U_c, in the present case of uniform density, is approximately[14,15] $U_c \approx (U_1 + U_2)/2$. The mean vortex spacing can be estimated using the relation,[15]

$$\frac{\overline{l}_n}{x} = 0.68\,\frac{1-r}{1+r}$$

where $r = U_2/U_1$ is the velocity ratio. The mean vortex passage frequency can now be estimated according to

$$\overline{f}_n = \frac{U_c}{0.68x\lambda}$$

where $\lambda = (1-r)/(1+r)$. Matching of the forcing frequency f and the mean vortex passage frequency $\overline{f}_n$ leads to the relation $\lambda x f/U_c \approx 1.47$ as an estimate of the downstream location where the layer thickness reaches a maximum and the large vortices are fully formed. This estimate agrees with the findings of Oster and Wygnanski[4] that the center of "region 2" (see the introduction) occurs at $\lambda x f/U_c \approx 1.5$.

In both cases of forcing the downstream region and the upstream region (see the next section), the passage frequency of the large vortices that are formed is the same as the forcing frequency. In other words, if l is the vortex spacing and f the forcing frequency, we obtain $fl/U_c = 1$. The vortex spacing can be readily obtained by measuring the separation distance between the vortices in Fig. 3. While there are general similarities between our results and the previous work on shear layer low-frequency forcing,[4,5] the growth rates observed here appear to be larger. Under low-frequency excitation, shear layer growth rate increases of up to a factor of two over the unforced layer have been reported.[9] In our data of Fig. 4, maximum spreading rates as high as three times the natural layer are indicated. Note also that, in most high-growth cases, the size of the structures has become comparable to the channel height. It is quite possible that the finite height of the channel may be restricting the growth of structures that might otherwise have grown to even larger sizes.

Upstream Influence

The growth of the shear layer in the region *upstream* of the airfoil is not affected by either the presence of the stationary airfoil or its oscillation at low frequencies; see Fig. 4. Measurements of the streamwise velocity at three stations in the upstream region show that the mean and rms profiles also remain unchanged when compared to the natural layer. Figure 8 shows one such comparison at a distance about one chord length upstream of the airfoil. For these low frequencies, the shear layer is divided into two regions: one upstream of the airfoil where the layer grows as in the natural case and the other downstream of the airfoil where the growth rate is substantially increased. The large mismatch of the airfoil oscillation frequency with the predominant natural frequencies in the shear layer in the upstream region of the airfoil is most likely the reason this portion of the layer remains unaffected.

Control over the structure and growth rate in the upstream part of the layer *can* be exercised if the forcing frequency is raised. Examples of forcing the upstream region are provided in Fig. 9. The photograph in this figure, corresponding to low-frequency forcing, also represents the flow patterns in cases of the natural layer and stationary airfoil, due to the insensitivity of this region to low-frequency excitation, as discussed previously. Figure 9 shows that forcing close to the natural frequency leads to the formation of a periodic, noninteracting array of vortices. These effects are similar to results obtained by previous excitation techniques where forcing was applied at the splitter plate trailing edge (e.g., see Refs. 5-7). In fact, using the present technique of forcing the upstream region, we have been able to observe many of the features documented in mixing layers that were forced by other means.[1]

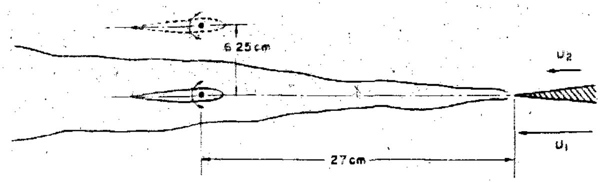
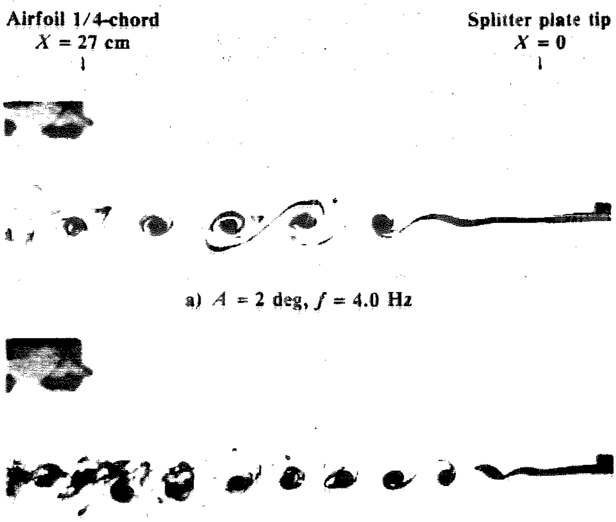


Fig. 10 Flow geometry with the airfoil inside and outside the shear layer.



a) A = 2 deg, f = 4.0 Hz

b) A = 2 deg, f = 6.0 Hz

Fig. 11 Upstream forcing with the airfoil outside the shear layer.

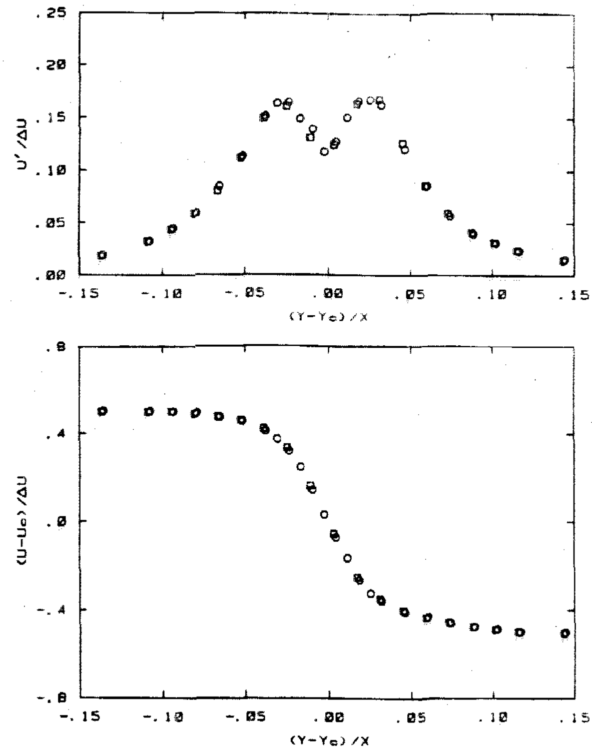
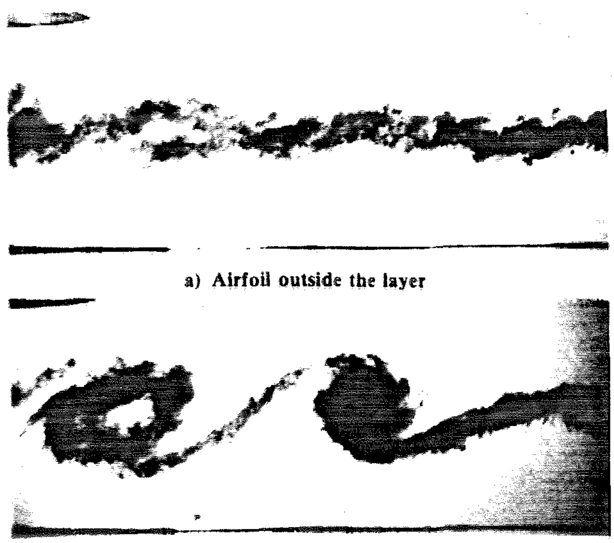


Fig. 12 Mean and rms velocity profiles at X = 18 cm, A = 2 deg, and f = 4.0 Hz (○ airfoil inside the layer, □ airfoil outside the layer).



a) Airfoil outside the layer

b) Airfoil inside the layer

Fig. 13 Effect of the airfoil position on downstream forcing (A = 2 deg, f = 0.347 Hz).

Coupling Mechanism

The oscillating airfoil can disturb the shear layer by at least two mechanisms. First, there is the "potential" disturbance generated by the motion of the airfoil. This is the disturbance that would be present even in the absence of the shear layer (i.e., an oscillating airfoil in the freestream) and is due to the oscillating bound circulation on the airfoil and the circulation of the resulting free vortices shed into the wake. The potential disturbance is transmitted everywhere in the flow, both upstream and downstream, instantaneously for the (present) case of an incompressible flow. Second is the disturbance caused by the interaction between the vorticity shed by the airfoil and that already present in the shear layer. This disturbance is convected only in the downstream direction. At low airfoil oscillation frequencies, the disturbance could take the form of a transverse oscillation imposed on the shear layer at the airfoil trailing edge. At higher frequencies, the airfoil-shed vorticity that concentrates into vortical structures[12,16] can interact with the shear layer large-scale vortices. Note that this discussion does not presume a linear interaction process. It should be stated that the vortex interaction mentioned above has, in principle, an upstream influence also. The influence is believed to be limited to the near vicinity of the airfoil, since the main contribution comes from high-order moments (poles) of the vorticity distribution whose induced velocity drops sharply with separation distance.

Forcing the upstream region, described earlier, can be explained very simply as being the result of the coupling of the airfoil's "potential" disturbance to the flow in the vicinity of the splitter plate trailing edge. This behavior would then be similar to the case of acoustic excitation in that the effective coupling occurs near the trailing edge of the splitter plate.[17,18] Is the large downstream increase of the layer growth rate under low-frequency excitation the result of coupling of the disturbance to the flow at the splitter plate or the direct interaction at the airfoil location by the second mechanism?

We attempted to answer this question by taking away the second coupling mechanism. This is done by removing the airfoil from the middle of the layer and placing it on the low-speed side outside the shear layer, as indicated in Fig. 10. Except for a minor reduction in the effective amplitude, the first mechanism is believed to be mostly unaffected by the change of position of the airfoil. The effects of forcing on the upstream region, with the new geometry, are shown in Fig. 11. It can be seen that the shear layer can be forced just as easily

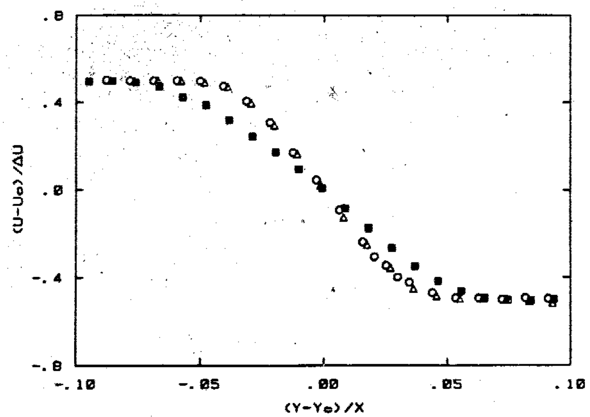


Fig. 14 Effect of the airfoil position on the mean velocity profile in the forced layer when $A = 2$ deg, $f = 0.347$ Hz, and $X = 135$ cm (○ natural, ■ airfoil inside the layer, △ airfoil outside the layer).

as before and the resulting flow, except for a region very near the airfoil, is the same as when the airfoil is in the middle of the layer. Measurements of the velocity at various locations in the upstream region show that the mean and rms profiles are identical, regardless of the airfoil position. One such comparison is shown in Fig. 12. On the other hand, the position of the airfoil is crucial in forcing the downstream region, as illustrated in Figs. 13 and 14. Moving the airfoil outside the shear layer appears to have also removed almost all the disturbances at the forcing frequency. With the airfoil in the new position, the shear layer does not grow into large sizes. The mean velocity profile is as in the natural case and the rms profile (not shown here) shows little change relative to the natural layer.

Based on the results described above, we conclude that forcing the upstream region can be thought of as being the result of the "potential" disturbances introduced by the oscillating airfoil. On the contrary, in the cases of forcing the downstream region, results show that the disturbances are coupled into the layer at the airfoil location and that the effect of the "potential" disturbances amplified throughout the layer is negligible.

Conclusions

The effects of a locally introduced disturbance on a turbulent plane mixing layer were investigated. Disturbances were generated by a two-dimensional pitching airfoil located downstream of the splitter plate trailing edge. Results show that the regions upstream and downstream of the airfoil can be selectively forced by the proper choice of the frequency. At low forcing frequencies, the region upstream is unaffected, while large increases in the shear layer spreading rate downstream of the disturbance source are observed. Forcing at high frequencies leaves the growth rate of the layer in the downstream region relatively unchanged (slight decrease compared to natural), whereas the flow structure in the upstream region is modified. Results suggest that forcing the upstream region is a consequence of the coupling of the airfoil's "potential" disturbance to the flow at the trailing edge of the splitter plate. This type of coupling is very weak in the case of low-frequency forcing of the downstream region. In this case, the direct transverse oscillations imposed on the shear layer locally at the airfoil trailing edge provide the coupling of the disturbance to the flow.

Acknowledgments

We thank our colleagues in the Aeronautics Department at Caltech for the many useful discussions and ideas. This work was initially supported under the Caltech President's Fund Grant PF-126, in collaboration with Dr. Donald Collins of the Caltech Jet Propulsion Laboratory. Subsequent support continued under the sponsorship of the Air Force Office of Scientific Research Grant AFOSR-84-0120.

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PLEASE NOTE!

Labels for downstream locations on figures 3, 6 are misplaced and those for figure 13 are missing. The labels for downstream locations X = 80 cm and X = 210 cm for all three figures should be located as indicated on the xerox copy of figure 6 attached.

Labels for downstream locations on figures 9, 11 are misplaced. The correct labels for X = 0 and X = 27 cm for these figures are indicated on the xerox copy of figure 9 attached.

A = 2 deg.

A = 4 deg.

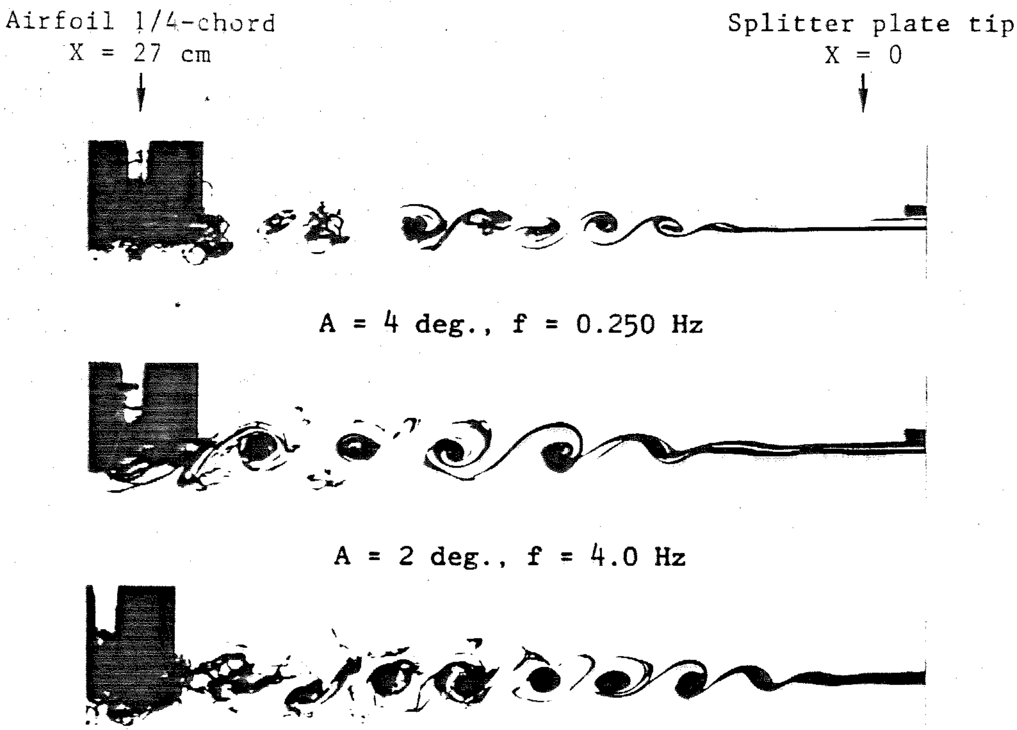
A = 6 deg.

X = 210 cm

X = 80 cm

Effect of the forcing amplitude on the shear layer structure and growth for f = 0.250 Hz.

Figure 6



A = 4 deg., f = 0.250 Hz

A = 2 deg., f = 4.0 Hz

A = 2 deg., f = 6.0 Hz

Effect of the pitching airfoil on the shear layer structure and growth in the region upstream of the airfoil.

Figure 9

Appendix C

AIAA'88

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A Cancellation Experiment in a Forced Turbulent Shear Layer

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AIAA/ASME/SIAM/APS
1st National Fluid Dynamics Congress
July 25-28, 1988/Cincinnati, Ohio

A CANCELLATION EXPERIMENT IN A FORCED TURBULENT SHEAR LAYER

88-3713-CP

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Abstract

Results are presented which demonstrate that it is possible to cancel, using feedback control techniques, the effects of an externally generated disturbance in a fully-developed turbulent two-dimensional shear layer.

Introduction

The evolution of plane mixing layers can be strongly affected by low-amplitude disturbances. The growth rate of a turbulent shear layer, for example, is effectively manipulated using controlled periodic excitation or forcing. These effects and other related phenomena have been recently reviewed by Ho & Huerre [1]. Forcing is usually achieved by introducing disturbances acoustically [2,3], mechanically by an oscillating flap [4-5], or oscillating one or both free-stream velocities [6-7].

Practically all of the turbulent mixing layer forcing studies to date may be classified as open-loop forcing of the turbulent layer. Successful manipulation of fully-developed turbulent flows through active, closed-loop, feedback control techniques has, to our knowledge, not yet been demonstrated. The possibility of active feedback control of turbulent flow would suggest new prospects of potentially significant applications such as turbulent mixing control and throttling combustion processes, drag reduction, pollution control, noise reduction, etc. It is further noted that discovering what is required to actively control a turbulent flow would be expected to reveal a great deal about the underlying dynamical processes at work within the flow. It should be mentioned that recent research in feedback control in fluid mechanics has demonstrated the potential of manipulating turbulence *transition* phenomena [8-12]. We believe that the possibility of feedback control of *fully-developed* turbulent flow has yet to be demonstrated and exploited.

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In the work described in this paper, we present a "proof of concept" experiment. We address the question of whether it is possible to cancel the effects of a controlled external disturbance which has been allowed to develop in a high Reynolds number, fully-developed turbulent shear layer. Exercising control over a turbulent flow that is forced in a known manner is an important first step before the control of a "natural" fully-developed turbulent flow can be attempted.

Experimental Facility & Instrumentation

The experiments were performed in the Low Speed Water Channel of the Graduate Aeronautical Laboratories of California Institute of Technology (GALCIT). The water channel was modified to generate a high aspect ratio 2-D shear layer, as indicated in Figure 1. The special insert used for this purpose followed the design of Dimotakis & Brown [13] and produced a shear layer with a velocity ratio, $r = U_2 / U_1$, of about 0.44 . The high-speed stream was set to a velocity of $U_1 = 20.6$ *cm/sec*, resulting in a Reynolds number, based on $(U_1 - U_2)$, of about 1150 per centimeter.

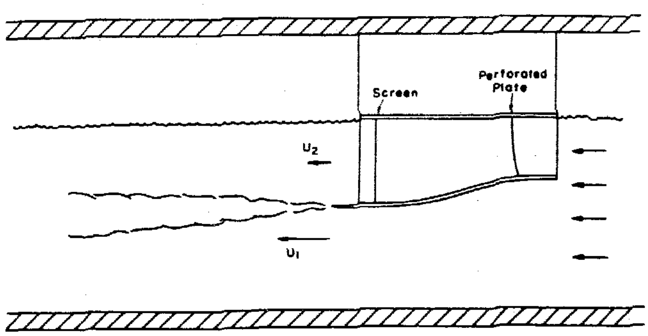


Figure 1. Schematic of the shear layer insert.

Disturbances were generated by two pitching airfoils that extended across the span (45 *cm*) of the water channel test section. The geometry of airfoil placement is shown in Figure 2. The first airfoil, a *NACA*–4415 with a chord of 4 *cm*, oscillated nearly sinusoidally about the 1/4-chord point with a prescribed amplitude and frequency. The drive mechanism was based on a DC motor and a linkage system and the angular position of the airfoil was monitored using a potentiometer. This assembly was used to launch a disturbance into the layer. Effects of this type of forcing on the turbulent shear layer have been described previously [5].

The second airfoil, a *NACA*–0012 with an 8–*cm* chord, was placed some distance downstream of the first airfoil. The driving system was designed such that this airfoil could execute arbitrary pitching motion [14]. A PDP-11/73 based computer monitored the motion of the first airfoil and computed a command signal which, through a D/A channel, drove the second airfoil.

The flow was visualized using food-coloring issuing from an injection port imbedded in the high-speed side of the shear layer insert and was subsequently recorded photographically using a 35 *mm* camera. The streamwise component of the velocity vector was measured by a single-channel, frequency-shifted laser Doppler velocimeter (LDV) in the dual scatter mode. We took advantage of frequency shifting for efficient band-limited filtering of the Doppler burst and also for lowering the signal dynamic range so that it could be measured by a Tracking Phase-Locked Loop. The output frequency of the phase-locked loop was measured by a Real Time Clock card interfaced to the same PDP-11/73 computer responsible for controlling the motion of the second airfoil. Other measurements using this LDV setup have been reported previously [5,14].

Results & Discussion

For the results described here, both airfoils extended across the shear layer span and were placed roughly in the middle of the layer, see Figure 2. We refer to the case when both airfoils are off (namely not oscillating) as the reference or unforced state. The flow, in this case, is not exactly the same as the "natural" layer without the two airfoils. Previous results have shown that the presence of such blades in the flow reduces the shear layer growth rate somewhat [5]. A photograph of the flow in the unforced case is illustrated in Figure 3a. The right and left edges of the photograph correspond to a range of downstream stations of $80\ cm < X < 210\ cm$ measured from the splitter plate trailing edge. This range is equivalent to $1053 < X / \theta_0 < 2763$, where θ_0 is the initial momentum thickness of the boundary layer on the high-speed side at the splitter plate tip. The width of the photograph in the cross-stream direction corresponds to the height of the water in the channel, roughly 42 *cm* in this case. All of the photographs shown in this paper have the same geometric arrangement as described above.

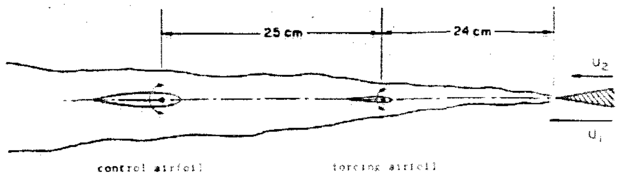
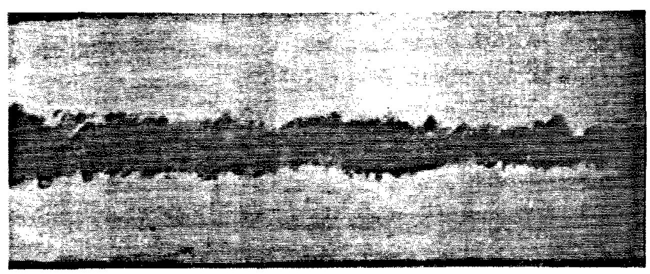


Figure 2. Flow geometry in the cancellation experiment.

The first airfoil, termed the forcing airfoil, was activated to pitch at a frequency of $f = 0.346\ Hz$ with an amplitude of about 3.6 degrees (i.e. peak-to-peak amplitude of 7.2 deg.). A photograph of the resulting forced turbulent shear layer is shown in Figure 3b. The selection of the frequency and amplitude values were based on previous work describing the response of a turbulent mixing layer forced by the technique used here [5]. Results are similar to those observed using other forcing techniques [2,4,6,7] and are briefly described below.

Earlier results [5] suggest that the airfoil oscillation frequency for which the largest effects are observed, at a given downstream station, appears to roughly correspond to the predominant local vortex passage frequency of the natural layer at that station. Forcing results in an increase of the shear layer spreading rate culminating in the formation of large vortices (e.g. see Figure 3b). As the frequency decreases/increases, the region of flow showing increased growth moves downstream/upstream. The passage frequency of the vortices that are finally formed is



(a) Unforced

(b) Forced

Figure 3. Turbulent shear layer in the reference (unforced) state and its response to forcing.

the same as the forcing frequency. In other words, if L is the vortex spacing, $U_c \approx (U_1 + U_2) / 2$ the convection speed and f the forcing frequency, then $f L / U_c = 1$.

The value of forcing frequency was selected such that the region of the layer that was most affected occured downstream of the forcing airfoil. For the operating conditions in this experiment, that would correspond to frequencies below approximately 2 Hz. Furthermore, the final vortex spacing L was chosen to be comparable or greater than the spacing between the two airfoils (25 cm). This reduced the forcing frequency to values below 0.6 Hz. The actual frequency of 0.346 Hz was finally selected to allow comparison with previous velocity measurements of the shear layer forced at this frequency (see Ref. 5). For comparison, we mention that the natural vortex shedding (instability) frequency at the splitter plate tip was about 6 Hz [5]. It should also be mentioned that the chord of the second airfoil becomes small relative to the forced vortex spacing, L, for the frequency selected here. This is believed to be a necessary requirement for effective cancellation.

The actual amplitude of the forcing airfoil does not affect the outcome of the cancellation experiment. It is only required that the amplitude be sufficient in order to force the layer. We point out, for completeness however, that according to previous work [5] the overall qualitative features of the forced layer, Figure 3b, are not expected to change if a different airfoil amplitude is used.

In an attempt to cancel the effects produced by the forcing airfoil a simple feedback scheme was tried. The motion of the second airfoil, or the control airfoil, was phase locked, under program control, to the motion of the first. A sinusoidal shape for the oscillation was selected and the amplitude and the phase difference between the two airfoils could be independently adjusted. Motion of the control airfoil was selected to be 180 degrees out of phase with the motion of the forcing airfoil, taking account also of the time delay required for the flow to convect the separation distance between the airfoils at a convection speed of $U_c \approx (U_1 + U_2) / 2$. The sequence of photographs in Figure 4a-c shows the results as the control airfoil is activated. Note that the layer immediately responds to the action of the control airfoil and resumes a growth rate comparable to the unforced case (compare Figures 3a and 4c).

These qualitative results are corroborated and quantified by LDV measurements of the streamwise component of velocity, see Figure 5. The measurements were carried out at a downstream station of X = 135 cm which corresponds to a location roughly half-way between the right and left edges of the photographs shown earlier.

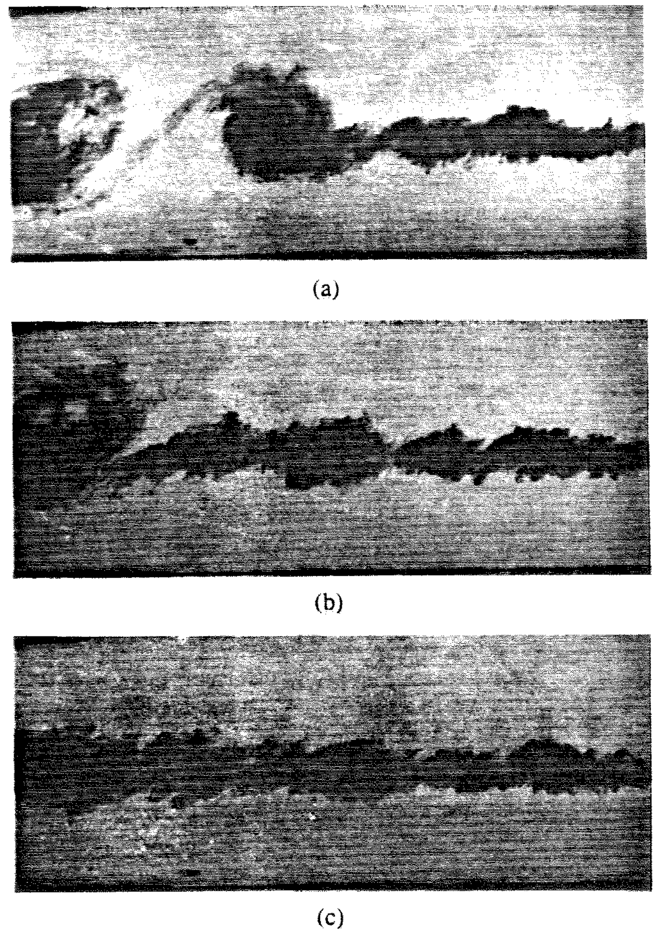


Figure 4. Response of the shear layer as the control airfoil is activated.

Note, in Figure 5, that both the mean velocity profile and the mean rms velocity fluctuation profile approach the "unforced" profiles upon activating the control airfoil.

It should be mentioned that success of the cancellation depends strongly on the proper choice of the amplitude and phase of the control airfoil. For example, insufficient amplitude results in partial cancellation. On the other hand, too large an amplitude turns the "control" airfoil into a new "forcing" airfoil. While one could employ automated parameter search and performance optimization algorithms, the optimum amplitude of the control airfoil, which was approximately 3.4 degrees for the results presented, was determined here by trial and error. Once the proper amplitude and phase were determined, the cancellation could be maintained for long periods of time. Data of Figure 5, as an example, were acquired over a period of about one hour.

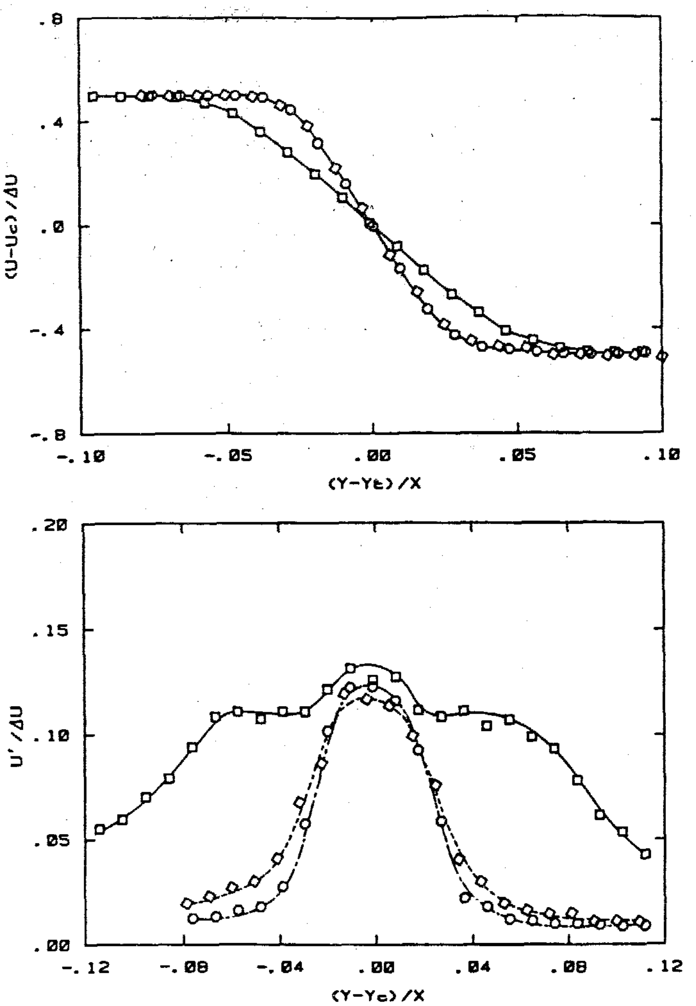


Figure 5. Mean and rms velocity profiles in the cancellation experiment; X = 135 *cm*.

○ both airfoils off,
□ forcing airfoil on, control airfoil off,
◇ control airfoil activated.

Moving the control airfoil in phase with the forcing airfoil was observed to result in an increase of the layer growth rate. The increase was, however, modest. This, we believe, is due to the finite height of the channel which may be restricting the growth of the layer. In Figure 3b, the size of the structure has become comparable to the channel height (visible at the left edge of the picture).

It seems tempting to argue for the success of the cancellation exepriment in terms of linear wave-cancellation ideas. It has been suggested [2,4,15] that the large-scale structure behavior in the forced turbulent mixing layer may be described in part by the linear inviscid stability theory. We emphasize, however, that the linear wave analysis, though *sufficient* to explain the present results, at least qualitatively, is probably not *necessary*. A numerical simulation of the cancellation experiment would help clarify the nonlinear vortex interaction between the vorticity shed by the oscillating control airfoil and that already present in the forced shear layer. The numerical simulation can take advantage of vortex tracing methods such as that used by Spalart & Leonard [16] in the case of oscillating airfoils in uniform free-stream. It should be noted that, for the present experiment, the non-uniform free-stream imposed by the forced turbulent free shear layer would have to be taken into account in the calculations of the vorticity shed from the trailing adge of the oscillating control airfoil.

These results, we believe, represent the first cancellation experiment in the spirit of previous experiments in the transition region of flat plate boudary layers [8-11], performed here, however, on a fully-developed turbulent shear flow. A major difference is that in the boundary layer experiments the flow is transitional and one could argue for the justifiability of a linear wave analysis (and linear wave superposition) in rather more rigorous terms. In the present case, we have demonstrated the cancellation of a disturbance which was allowed to grow amidth other nonlinear processes in a fully-developed, turbulent shear layer.

Conclusions

It was shown that it is possible to cancel the effects of an artificially generated disturbance in a fully-developed turbulent shear layer. In the experiment, a pitching airfoil launched a disturbance into the layer which resulted in a large increase of the layer growth rate. In the cancellation experiment, a second airfoil was placed downstream of the first. Pitching the second airfoil at the proper phase relative to the first and also at the right amplitude effectively cancelled the disturbances introduced by the first airfoil.

This, we believe, is the first cancellation experiment in the spirit of previous experiments in the transition region of flat plate boundary layers, performed here, however, on a fully-developed turbulent shear flow.

Acknowledgements

We would like to thank our colleagues in the Aeronautics Department at Caltech for the many useful discussions and ideas. This work was initially supported under the Caltech President's Fund Grant PF-126, in collaboration with Dr. Donald Collins of the Caltech Jet Propulsion Laboratory. Subsequent support continued under the sponsorship of the Air Force Office of Scientific Research Grant No. AFOSR-84-0120.

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